
# QNET DC Motor Control

## Workbook

QNET DCMCT

*Student Version*

Quanser Inc.
2011

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# Contents

# 1 INTRODUCTION

The DC Motor Control Trainer is shown in Figure 1.1. The system consists of a direct-current motor with an encoder and an inertia wheel on the motor shaft. The motor is driven using a pulse-width modulated (PWM) power amplifier. The power to the amplifier is delivered using the QNET power cable from a wall transformer and the encoder is powered by the ELVIS unit. Signals to and from the system are available on a header and on standard connectors for control via a Data Acquisition (DAQ) card. The control variable is the voltage to the drive amplifier of the system and the output is either the wheel speed or the angle of the wheel. Disturbances can be introduced manually by manipulating the wheel or digitally through LabVIEW®.

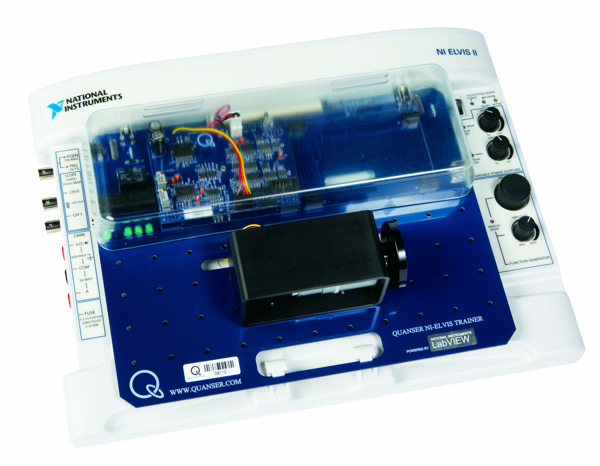


Figure 1.1: QNET DC motor control trainer (DCMCT)

There are three experiments: modeling, speed control, and position control. The experiments can be performed independently.

**Topics Covered**

- Modeling a DC motor experimentally
- PID Control
- Position control
- Speed control
- Disturbance rejection

**Prerequisites**
In order to successfully carry out this laboratory, the user should be familiar with the following:

- Transfer function fundamentals, e.g. obtaining a transfer function from a differential equation.
- Using LabVIEW®to run VIs.

# 2 MODELING

## 2.1 Background

### 2.1.1 Bump Test

The bump test is a simple test based on the step response of a stable system. A step input is given to the system and its response is recorded. As an example, consider a system given by the following transfer function:

$$\frac{Y(s)}{U(s)} = \frac{K}{\tau s + 1} \tag{2.1}$$

The step response shown in Figure 2.1 is generated using this transfer function with $K = 5$ rad/V.s and $\tau = 0.05$ s.

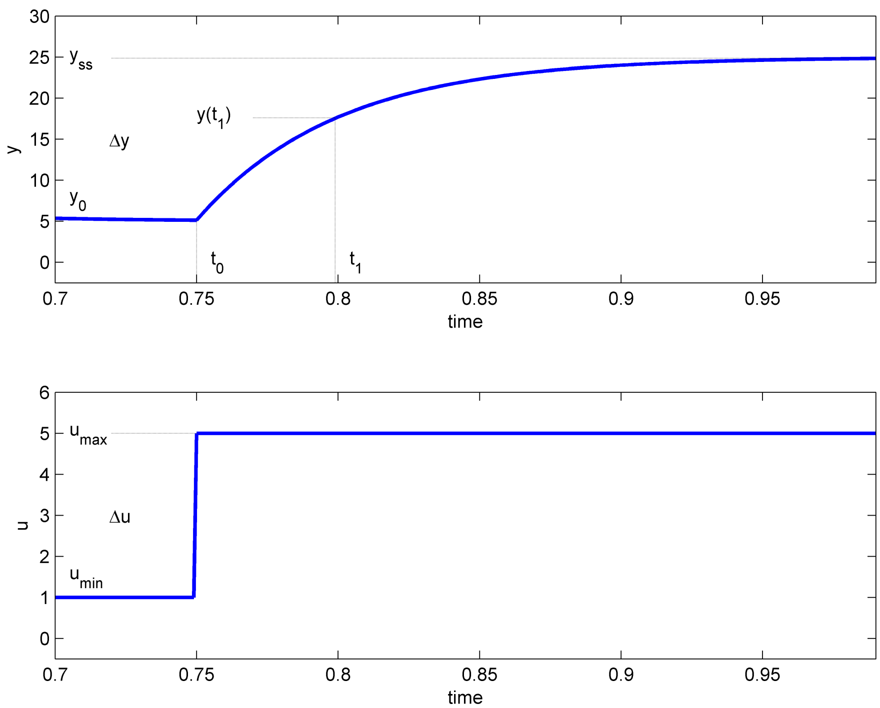


Figure 2.1: Input and output signal used in the bump test method

The step input begins at time $t_0$. The input signal has a minimum value of $u_{min}$ and a maximum value of $u_{max}$. The resulting output signal is initially at $y_0$. Once the step is applied, the output tries to follow it and eventually settles at its steady-state value $y_{ss}$. From the output and input signals, the steady-state gain is

$$K = \frac{\Delta y}{\Delta u} \tag{2.2}$$

where $\Delta y = y_{ss} - y_0$ and $\Delta u = u_{max} - u_{min}$. In order to find the model time constant, $\tau$, we can first calculate where the output is supposed to be at the time constant from:

$$y(t_1) = 0.632 y_{ss} + y_0 \tag{2.3}$$

Then, we can read the time $t_1$ that corresponds to $y(t_1)$ from the response data in Figure 2.1. From the figure we can see that the time $t_1$ is equal to:

$$t_1 = t_0 + \tau \tag{2.4}$$

From this, the model time constant can be found as:

$$\tau = t_1 - t_0 \tag{2.5}$$

### 2.1.2 Model Validation

When the modeling is complete it can be validated by running the model and the actual process in open-loop. That is, the open-loop voltage is fed to both the model and the actual device such that both the simulated and measured response can be viewed on the same scope. The model can then be adjusted to fit the measured motor speed by fine-tuning the modeling parameters.

See Wikipedia for more information on electric motor, mathematical model, transfer function, and LTI system theory.

## 2.2 Modeling Virtual Instrument

Applying a voltage to the DC motor and examining its angular rate is investigated in the laboratory. The model simulation is ran in parallel with the actual system to allow for model tuning and validation. The LabVIEW virtual instrument for modeling is shown in Figure 2.2. Figure 2.3 shows the graphs-view of the VI, which is used to take measurements.

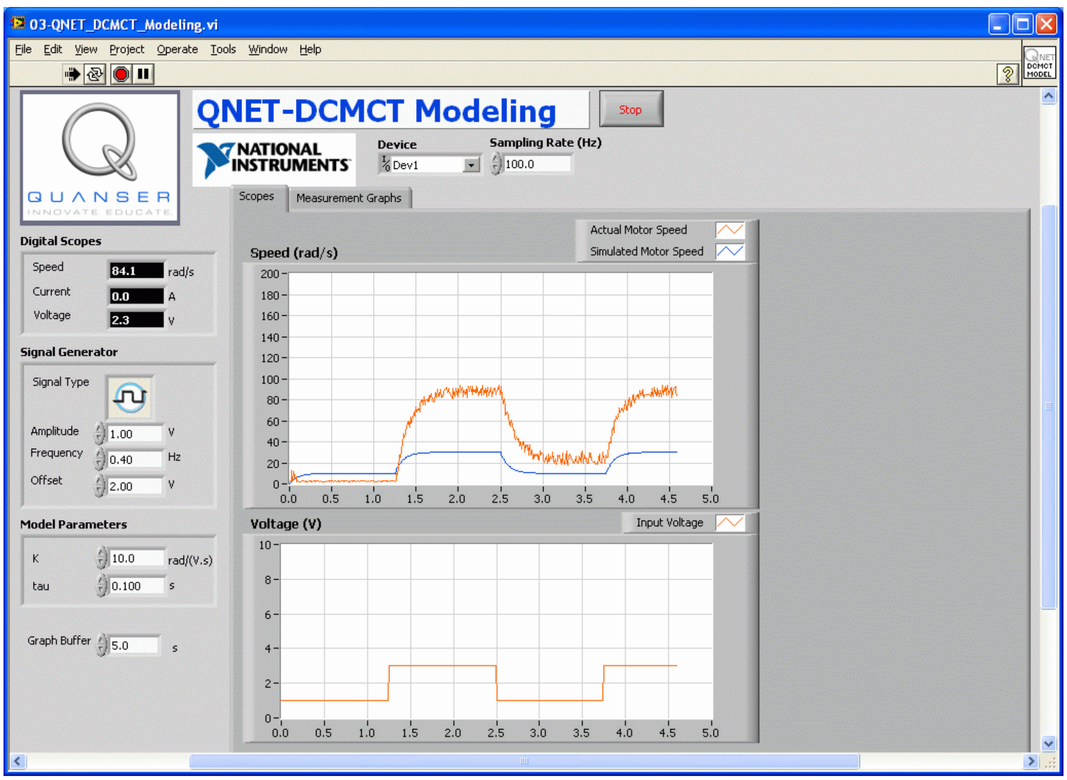


Figure 2.2: LabVIEW VI for modeling QNET DC motor

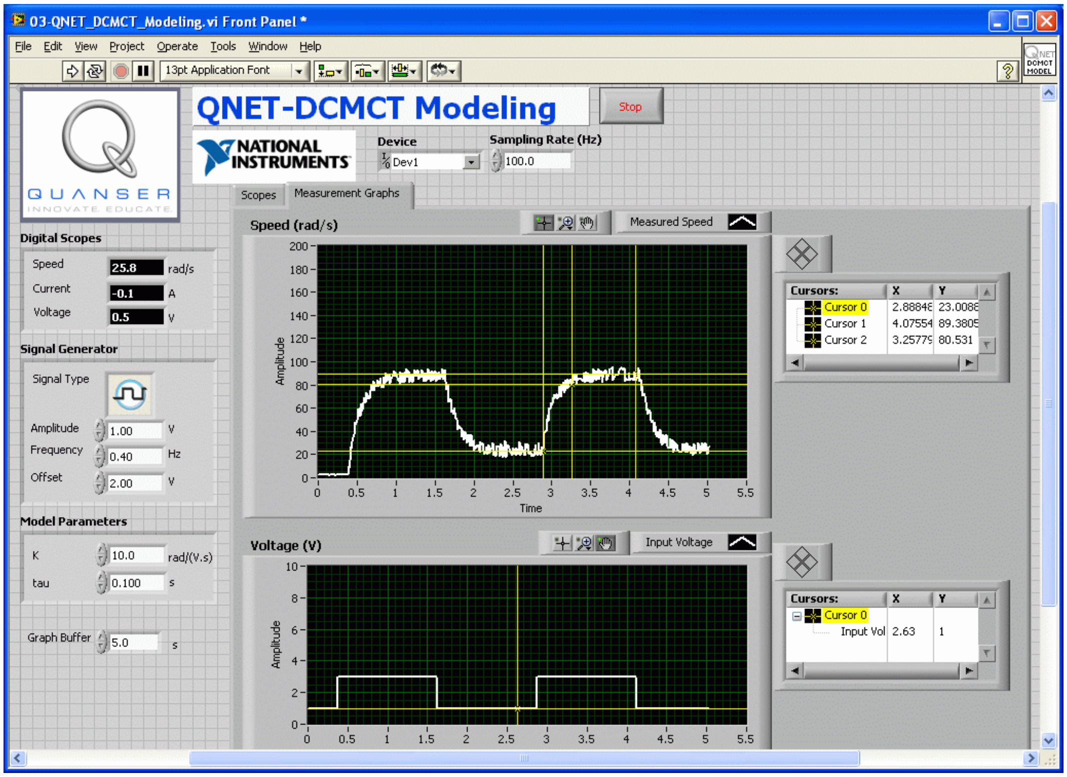


Figure 2.3: QNET DCMCT Modeling VI: sample response in Measurement Graphs

## 2.3 Lab 1: Bump Test [60 min]

1. Ensure the QNET DCMCT Modeling VI is open and configured as described in Section 5.2. **Make sure the correct *Device* is chosen.**
2. Run the QNET_DCMCT_Modeling.vi. The DC motor should begin spinning and the scopes on the VI should appear similarity as shown in Figure 2.2.
3. In the *Signal Generator* section set
   - Amplitude = 2.0 V
   - Frequency = 0.40 Hz
   - Offset = 3.0 V
4. Once you have collected a step response, click on the *Stop* button to stop running the VI.
5. Attach the responses in the *Speed (rad/s)* and *Voltage (V)* graphs. See the QNET VI LabVIEW Hints section in the QNET User Manual for information on how to export a chart or graph to the clipboard.
6. Select the *Measurement Graphs* tab to view the measured response, similarly as depicted in 5.2.
7. Use the responses in the *Speed (rad/s)* and *Voltage (V)* graphs to compute the steady-state gain of the DC motor. See Section 2.1.1 for details on how to find the steady-state gain from a step response. Finally, you can use the *Graph Palette* for zooming functions and the *Cursor Palette* to measure data. See the LabVIEW help for more information on these tools.
8. Based on the bumptest method, find the time constant. See Section 2.1.1 for details on how to find the time constant of the step response.
9. Enter the steady-state gain and time constant values found in this section in Table 1. These are called the bumptest model parameters.

## 2.4 Lab 2: Model Validation [45 min]

1. Ensure the QNET DCMCT Modeling VI is open and configured as described in Section 5.2. **Make sure the correct *Device* is chosen.**
2. Run the QNET_DCMCT_Modeling.vi. You should hear the DC motor begin running and the scopes on the VI should appear similarity as shown in Figure 7.
3. In the *Signal Generator* section set:
   - Amplitude = 2.0 V
   - Frequency = 0.40 Hz
   - Offset = 3.0 V
4. In the *Model Parameters* section of the VI, enter the bumptest model parameters, $K$ and $\tau$, that were found in Section 2.3. The blue simulation should match the red measured motor speed more closely.
5. Attach the *Speed (rad/s)* and *Voltage (V)* chart responses from the *Scopes* tab.
6. How well does your model represent the actual system? If they do not match, name one possible source for this discrepancy.
7. Tune the steady-state gain, *K*, and time constant, *tau*, in the *Model Parameters* section so the simulation matches the actual system better. Enter both the bumptest and tuned model parameters in Table 1.

## 2.5 Results

| Description | Symbol | Value | Unit |
|---|---|---|---|
| **Section 2.3: Bumptest Modeling** | | | |
| Motor steady-state gain | $K_{e,b}$ | | rad/s |
| Motor time constant | $\tau_{e,b}$ | | s |
| **Section 2.4: Model Validation** | | | |
| Motor steady-state gain | $K_{e,v}$ | | rad/s |
| Motor time constant | $\tau_{e,v}$ | | s |

Table 1: QNET DCMCT Modeling results summary

# 3 SPEED CONTROL

## 3.1 Background

The speed of the DC motor is controlled using a proportional-integral control system. The block diagram of the closed-loop system is shown in Figure 3.1.

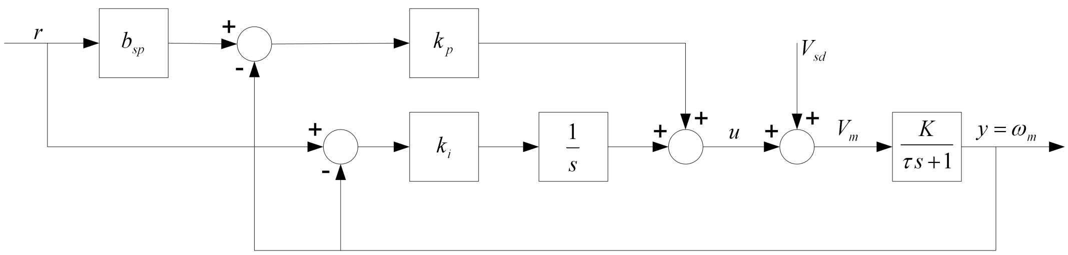


Figure 3.1: DC Motor PI closed-loop block diagram

The transfer function representing the DC motor speed-voltage relation in Equation 3.1 is used to design the PI controller. The input-output relation in the time-domain for a PI controller with set-point weighting is

$$u = k_p\left(b_{sp}r - y\right) + \frac{k_i\left(r - y\right)}{s} \tag{3.1}$$

where $k_p$ is the proportional gain, $k_i$ is the integral gain, and $b_{sp}$ is the set-point weight. The closed loop transfer function from the speed reference, $r$, to the angular motor speed output, $\omega_m$, is

$$G_{\omega,r}(s) = \frac{K(k_p b_{sp} s + k_i}{\tau s^2 + (K k_p + 1)s + K k_i} \tag{3.2}$$

The standard desired closed loop characteristic polynomial is

$$s^2 + 2\zeta\omega_0 + \omega_0^2 \tag{3.3}$$

where $\omega_0$ is the undamped closed loop frequency and $\zeta$ is the damping ratio. The characteristic equation in 3.2, i.e. the denominator of the transfer function, can match the desired characteristic equation in 3.3 with the following gains:

$$k_p = \frac{-1 + 2\,\zeta\,\omega_0\,\tau}{K} \tag{3.4}$$

and

$$k_i = \frac{\omega_0^2\,\tau}{K} \tag{3.5}$$

Large values of $\omega_0$ give large values of controller gain. The damping ratio, $\zeta$, and the set-point weight parameter, $b_{sp}$, can be used to adjust the speed and overshoot of the response to reference values.

There is no tachometer sensor present on the QNET DC motor system that measures the speed. Instead the amplifier board has circuitry that computes the derivative of the encoder signal, i.e. a digital tachometer. However to minimize the noise of the measured signal and increase the overall robustness of the system, the first-order low-pass filter

$$\omega_m = \frac{\omega_{meas}}{T_f s + 1}$$

is used. Parameter $T_f$ is the filter time constant that determines the cutoff frequency and $\omega_{meas}$ is the measured speed signal.

## 3.2 Speed Control Virtual Instrument

Tracking a square wave with various PD gains are discussed in the laboratory as well as the effects of set-point weighting and integrator windup. The steady-state errors due to triangular references are also assessed. The virtual instrument for speed control is shown in Figure 3.2.

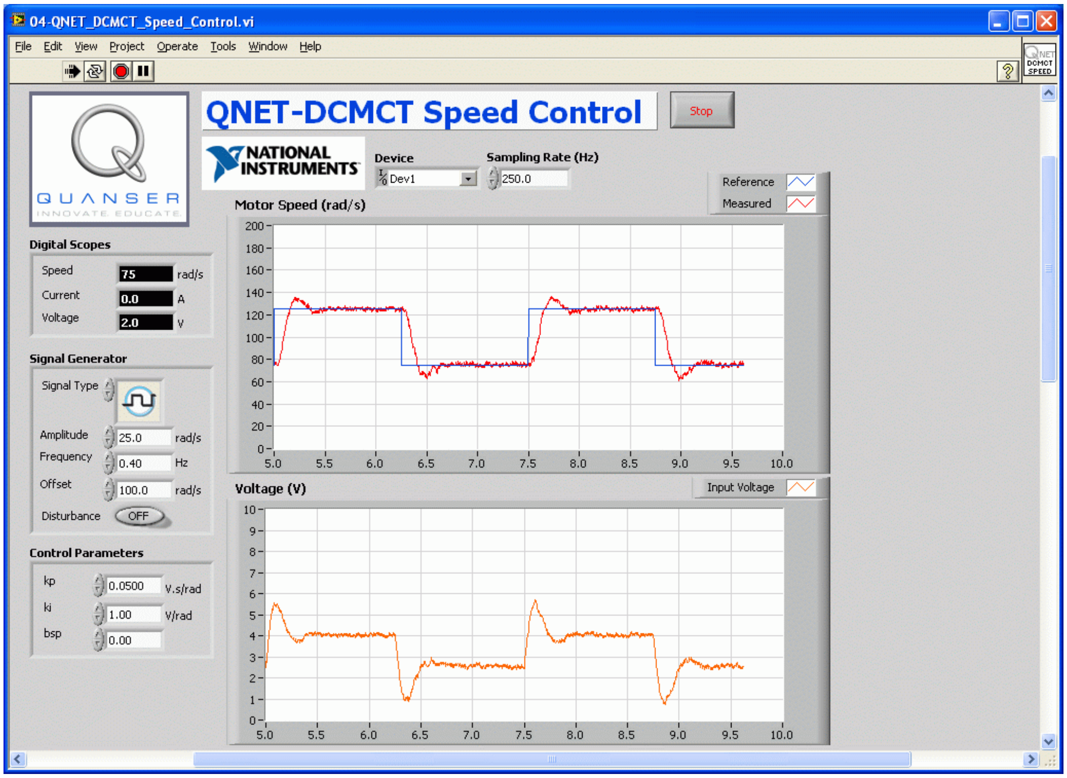


Figure 3.2: Virtual instrument for DC motor speed control

## 3.3 Lab 1: Qualitative PI Control [30 min]

1. Ensure the QNET_DCMCT_Speed_Control.vi is open and configured as described in Section 5.3. **Make sure the correct *Device* is chosen.**
2. Run the QNET_DCMCT_Speed_Control.vi. The motor should begin rotating and the scopes should look similar as shown in Figure 3.2.
3. In the *Signal Generator* section set:
   - Signal Type = 'square wave'
   - Amplitude = 25.0 rad/s
   - Frequency = 0.40 Hz
   - Offset = 100.0 rad/s
4. In the *Control Parameters* section set:
   - kp = 0.0500 V.s/rad
   - ki = 1.00 V/rad
   - bsp = 0.00
5. Examine the behaviour of the measured speed, shown in red, with respect to the reference speed, shown in blue, in the *Speed (rad/s)* scope. Explain what is happening.

6. Increment and decrement *kp* by steps of 0.005 V.s/rad.

7. Look at the changes in the measured signal with respect to the reference signal. Explain the performance difference of changing $k_p$.

8. Set *kp* to 0 V.s/rad and *ki* to 0 V/rad. The motor should stop spinning.

9. Increment the integral gain, *ki*, by steps of 0.05 V/rad. Vary the integral gain between 0.05 V/rad and 1.00 V/rad.

10. Examine the response of the measured speed in the *Speed (rad/s)* scope and compare the result when *ki* is set low to when it is set high.

11. Stop the VI by clicking on the *Stop* button.

## 3.4 Lab 2: PI Control According to Specifications [60 min]

### 3.4.1 Pre-Lab Exercises

1. Using the equations outlined in the *Peak Time and Overshoot* section of the QNET Practical Control Guide, calculate the expected peak time, $t_p$, and percent overshoot, PO, given the following *Speed Lab Design (SLD)* specifications:

   - $\zeta$ = 0.75
   - $\omega_0$= 16.0 rad/s

   **Optional**: You can also design a VI that simulates the DC motor first-order model with a PI control and have it calculate the peak time and overshoot.

2. Calculate the proportional, $k_p$, and integral, $k_i$, control gains according to the model parameters found in Section 2 and the SLD specifications.

### 3.4.2 In-Lab Experiment

1. Ensure the QNET_DCMCT_Speed_Control.vi is open and configured as described in Section 5.3. **Make sure the correct *Device* is chosen.**

2. Run the QNET_DCMCT_Speed_Control.vi. The motor should begin spinning and the scopes should look similar as shown in Figure 3.2.

3. In *Signal Generator* set:

   - Signal Type ='square wave'
   - Amplitude = 25.0 rad/s
   - Frequency = 0.40 Hz
   - Offset = 100.0 rad/s

4. In the *Control Parameters* section, enter the SLD PI control gains found in Step 2and make sure *bsp* = 0.

5. Stop the VI when you collected two sample cycles by clicking on the *Stop* button.

6. Capture the measured SLD speed response. Make sure you include both the *Speed (rad/s)* and the control signal *Voltage (V)* scopes.

7. Measure the peak time and percentage overshoot of the measured SLD response. Are the specifications satisfied?

8. What effect does increasing the specification $\zeta$ have on the measured speed response? How about on the control gains? Use the damping ratio equation given in the *Peak Time and Overshoot* section of the QNET Practical Control Guide for more help if needed.

9. What effect does increasing the specification *w0* have on the measured speed response and the generated control gains? Use the natural frequency equation found in the *Peak Time and Overshoot* section of the QNET Practical Control Guide for more help if needed.

## 3.5 Lab 3: Set-Point Weight [15 min]

1. Ensure the QNET_DCMCT_Speed_Control.vi is open and configured as described in Section 5.3. **Make sure the correct *Device* is chosen.**

2. Run the QNET_DCMCT_Speed_Control.vi. The motor should begin rotating.

3. In the *Signal Generator* section set:
   - Signal Type = 'square wave'
   - Amplitude = 25.0 rad/s
   - Frequency = 0.40 Hz
   - Offset = 100.0 rad/s

4. In the *Control Parameters* section set:
   - kp = 0.050 V.s/rad
   - ki = 1.50 V/rad
   - bsp= 0.00

5. Increment the set-point weight parameter *bsp* in steps of 0.05. Vary the parameter between 0 and 1.

6. Examine the effect that raising $b_{sp}$ has on the shape of the measured speed signal in the *Speed (rad/s)* scope. Explain what the set-point weight parameter is doing.

7. Stop the VI by clicking on the *Stop* button.

## 3.6 Lab 4: Tracking Triangular Signals [20 min]

1. Ensure the QNET_DCMCT_Speed_Control.vi is open and configured as described in Section 5.3. **Make sure the correct *Device* is chosen.**

2. Run the QNET_DCMCT_Speed_Control.vi. The motor should begin rotating.

3. In *Signal Generator* set:
   - Signal Type = 'triangular wave'
   - Amplitude = 50.0 rad/s
   - Frequency = 0.40 Hz
   - Offset = 100.0 rad/s

4. In the *Control Parameters* section set:
   - kp = 0.20 V.s/rad
   - ki = 0.00 V/rad
   - bsp = 1.00

5. Compare the measured speed and the reference speed. Explain why there is a tracking error.

6. Increase *ki* to 0.1 V/rad and examine the response. Vary *ki* between 0.1 V/rad and 1.0 V/rad.

7. What effect does increasing *ki* have on the tracking ability of the measured signal? Explain using the observed behaviour in the scope.

8. Stop the VI by clicking on the *Stop* button.

## 3.7 Results

| Description | Symbol | Value | Unit |
|---|---|---|---|
| **Section 3.4: PI Control Design** | | | |
| Model gain used | $K$ | | rad/s |
| Model time constant used | $\tau$ | | s |
| Proportional gain | $k_p$ | | V/(rad/s) |
| Integral gain | $k_i$ | | V/rad) |
| Measured peak time | $t_p$ | | s |
| Measured percent overshoot | $PO$ | | % |

Table 2: QNET DCMCT Speed Control results summary

# 4 POSITION CONTROL

## 4.1 Background

Control of motor position is a natural way to introduce the benefits of derivative action. In this experiment a proportional-integral-derivative controller is designed according to specifications. The closed-loop PID control block diagram is shown in Figure 4.1.

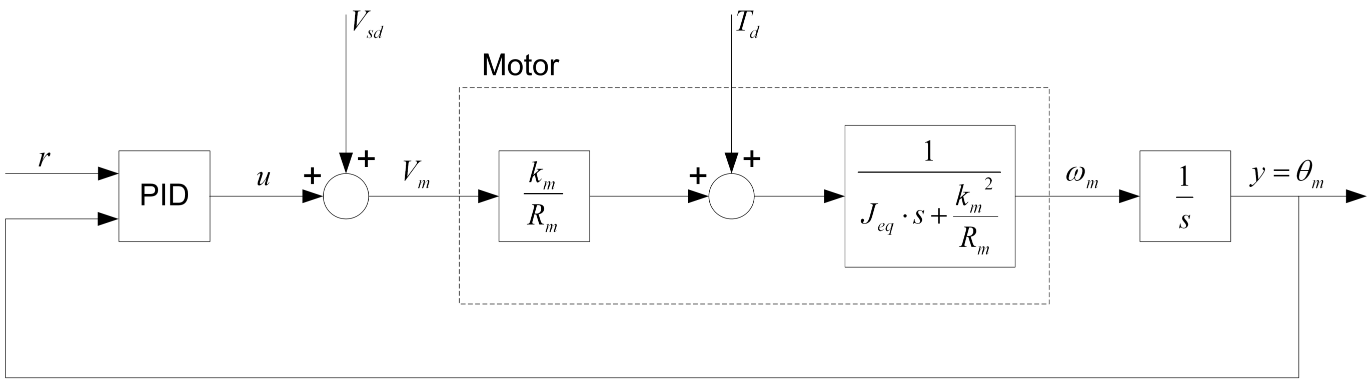


Figure 4.1: DC Motor PI closed-loop block diagram

The two-degree of freedom PID transfer function inside the PID block in Figure 4.1 is

$$u = k_p \left(b_{sp} r(t) - y(t)\right) + k_i \int_0^t \left(r(\tau) - y(\tau)\right) d\tau + k_d \left(b_{sd} \dot{r}(t) - \dot{y}(t)\right) \tag{4.1}$$

where $k_p$ is the position proportional control gain, $k_d$ is the derivative control gain, $k_i$ is the integral control gain, $b_{sp}$ is the set-point weight on the reference position $r(t)$, and $b_{sd}$ is the set-point weight on the velocity reference of $r(t)$.

The dotted box labeled *Motor* in Figure 4.1 is the motor model in terms of the back-emf motor constant $k_m$, the electrical motor armature resistance $R_m$, and the equivalent moment of inertia of the motor pivot $J_{eq}$. The direct disturbance applied to the inertial wheel is represented by the disturbance torque variable $T_d$ and the simulated disturbance voltage is denoted by the variable $V_{sd}$.

### 4.1.1 PD Control Design

The behaviour of the controlling the motor position is first analyzed using a PD control. By setting $k_i = 0$ in the PID control equation Equation 4.1 and taking its Laplace transform, the PD transfer transfer function is

$$u = k_p(r - y) + k_d s(b_{sd} r - y) \tag{4.2}$$

Combining the position process model

$$\frac{\Theta_m(s)}{V_m(s)} = \frac{K}{s(\tau s + 1)}$$

with the PD control Equation 4.2 gives the closed-loop transfer function of the motor position system

$$G_{\theta,r}(s) = \frac{K\ (k_p + b_{sd} k_d s)}{\tau s^2 + (1 + K\, k_d)\, s + K\, k_p}$$

Similarly to the speed control laboratory, the standard characteristic function shown in Equation 3.3 can be achieved by setting the proportional gain to

$$k_p = \frac{\omega_0^2\, \tau}{K} \tag{4.3}$$

and the derivative gain to

$$k_d = \frac{-1 + 2\,\zeta\,\omega_0\,\tau}{K}. \tag{4.4}$$

### 4.1.2 Response to Load Disturbance

Next, the behaviour of the PID closed-loop system when it is subjected to a disturbance is examined. The block diagram shown in Figure 4.2 represents the load disturbance to position response when $b_{sp}$ and $b_{sd}$ in the PID in Equation 4.1 are both set to 1.

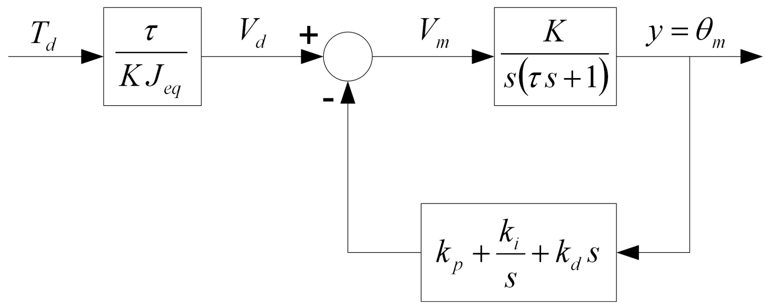


Figure 4.2: PID closed-loop block diagram to a load disturbance input

The closed-loop disturbance to position transfer function is

$$G_{\theta,T}(s) = \frac{\tau\, s}{J_{eq}(\tau\, s^3 + (1 + K\, k_d)\, s^2 + K\, k_p\, s + K\, k_i)} \tag{4.5}$$

Given a step disturbance with an amplitude of $T_{d0}$

$$T_d(s) = \frac{T_{d0}}{s}$$

the steady-state angle of the closed-loop system is

$$\theta_{ss} = T_{d0}\left(\lim_{s \to 0} G_{\theta,T}(s)\right)$$

The steady-state angle of the PD control, that is when $k_i = 0$ in 4.5, is

$$\theta_{ss\_PD} = \frac{\tau T_{d0}}{J_{eq} K k_p},$$

and the steady-state angle with integral action is

$$\theta_{ss\_PID} = 0.$$

Thus when the system is subjected to a disturbance, a constant steady-state error is observed when using the PD control system. However, the disturbance is rejected when integral control is used and the steady-state angle eventually goes to zero.

PID control design involves using the standard characteristic equation for a third-order system

$$(s^2 + 2\zeta\omega_0 + \omega_0^2)(s + p_0) = s^3 + (2\zeta\omega_0 + p_0)s^2 + (\omega_0^2 + 2\zeta\omega_0 p_0)s + \omega_0^2 p_0 \tag{4.6}$$

where $\omega_0$ is the natural frequency, $\zeta$ is the damping ratio, and $p_0$ is a zero. The characteristic equation of the closed-loop PID transfer function, i.e. the denominator of the transfer function 4.5, is

$$s^3 + \frac{K k_d + 1}{\tau} s^2 + \frac{K k_p}{\tau} s + \frac{K k_i}{\tau} \tag{4.7}$$

The PID characteristic equation 4.7 matches 4.6 using the proportional gain

$$k_p = \frac{\omega_0 \tau (\omega_0 + 2\zeta p_0)}{K}$$

the derivative gain

$$k_d = \frac{-1 + 2\zeta \omega_0 \tau + p_0 \tau}{K}$$

and the integral gain

$$k_i = \frac{\omega_0^2 p_0 \tau}{K}$$

By varying the zero location, $p_0$, the time required by the closed-loop response to recover from a disturbance is changed.

## 4.2 Position Control Virtual Instrument

Tracking a reference position square wave using PID control is first examined in this laboratory. Then, disturbance effects using PD and PID are studied through direct manual interaction or a simulated using a control switch in the VI. The LabVIEW virtual instrument for position control is shown in Figure 4.3.

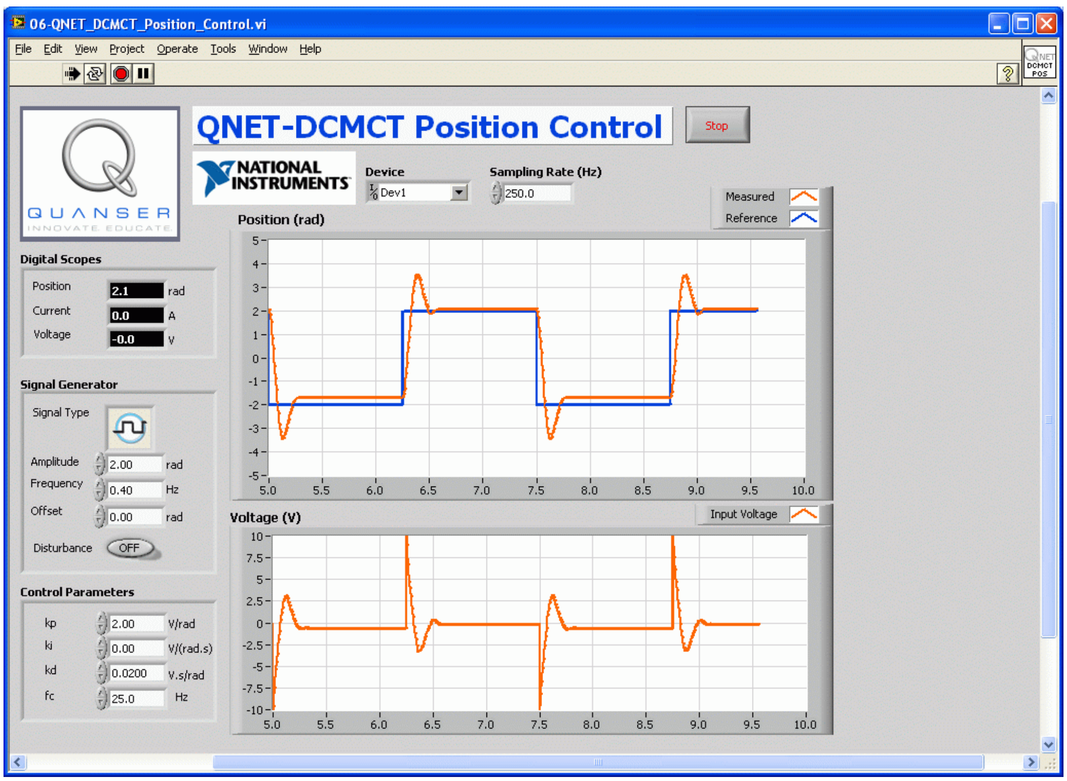


Figure 4.3: Virtual instrument for DC motor position control

See Wikipedia for more information on motion control, control theory and PID.

## 4.3 Lab 1: Qualitative PD Control [30 min]

1. Make sure the QNET_DCMCT_Position_Control.vi is open and configured as described in Section 5.4. **Make sure the correct *Device* is chosen.**

2. Run the QNET_DCMCT_Position_Control.vi. The DC motor should be rotating back and forth and the scopes on the VI should appear similarity as shown in Figure 4.3.
3. In the *Signal Generator* section set:
   - Amplitude = 2.00 rad
   - Frequency = 0.40 Hz
   - Offset = 0.00 rad
4. In the *Control Parameters* section set:
   - kp = 2.00 V/rad
   - ki = 0.00 V/rad
   - kd = 0.00 V.s/rad
5. Change the proportional gain, *kp*, by steps of 0.25 V/rad. Try the following gains: *kp* = 0.5, 1, 2, and 4 V/rad.
6. Examine the behaviour of the measured position (red line) with respect to the reference position (blue line) in the *Position (rad)* scope. Explain what is happening.
7. Describe the steady-state error to a step input.
8. Increment the derivative gain, *kd*, by steps of 0.01 V.s/rad.
9. Look at the changes in the measured position with respect to the desired position. Explain what is happening.
10. Stop the VI by clicking on the *Stop* button.

## 4.4 Lab 2: PD Control according to Specifications [60 min]

### 4.4.1 Pre-Lab Exercises

1. Using the equations in the Peak Time and Overshoot section of the QNET Practical Control Guide, calculate the expected peak time, $t_p$, and percentage overshoot, $PO$, given
   - $\zeta$ = 0.60
   - $\omega_0$ = 25.0 rad/s
   - $p_0$ = 0.0

   **Optional**: You can also design a VI that simulates the DC motor first-order model with a PD control and have it calculate the peak time and overshoot.
2. Calculate the proportional, $k_p$, and derivative, $k_d$, control gains according to the model parameters found in Section 2.4 and the specifications above.

### 4.4.2 In-Lab Experiment

1. Make sure the QNET_DCMCT_Position_Control.vi. is open and configured as described in Section 5.4. **Make sure the correct *Device* is chosen.**
2. Run the QNET_DCMCT_Position_Control.vi. You should see the DC motor rotating back and forth.
3. In the *Signal Generator* section set:
   - Amplitude = 2.00 rad
   - Frequency = 0.40 Hz

- Offset = 0.00 rad

4. In the *Control Parameters* section, set the PD gains found in Step 2 in Section 4.4.1.
5. Capture the position response found in the *Position (rad)* scope and and control signal used in the *Voltage (V)* scope.
6. Measure the peak time and percentage overshoot of the measured position response. Are the specifications satisfied?
7. What effect does changing the specification zeta have on the measured position response and the generated control gains? See the *Peak Time and Overshoot* section of the QNET Practical Control Guide for more help.
8. What effect does changing the specification $\omega_0$ have on the measured position response and the generated control gains? See the *Peak Time and Overshoot* section of the QNET Practical Control Guide for more help.
9. Stop the VI by clicking on the *Stop* button.

## 4.5 Lab 3: Response to Load Disturbance [60 min]

### 4.5.1 Pre-Lab Exercises

1. In the *Response to Load Disturbance* section of the QNET Practical Control Guide, the load disturbance to motor position closed-loop PID block diagram is found. Consider the same regulation system, $r = 0$, when $b_{sp} = 1$ and $b_{sd} = 1$ and show the block diagram representing the simulated disturbance to motor position closed-loop interaction (in this case $T_d = 0$).
2. Find the closed-loop PID transfer function describing the position of the motor with respect to the simulated disturbance voltage: $G_{\theta,V_{sd}}(s) = \Theta(s)/V_{sd}(s)$.
3. Find the steady-state motor angle due to a simulated disturbance step of $V_{sd} = V_{sd0}/s$.
4. A step of $V_{sd} = V_{sd0}/s$ with $V_{sd0} = 3$ V is added to the motor voltage to simulate a disturbance torque. Evaluate the steady-state angle of the motor when a PD controller is used with the gains *kp* = 2 V/rad and *kd* = 0.02 V.s/rad. Then, calculate the steady-state angle when using a PID controller with the gains *kp* = 2 V/rad, *kd* = 0.02 V.s/rad, and *ki* = 1 V/rad/s.

   **Optional**: You can also design a VI that simulates the DC motor first-order model with a PID control and a step disturbance and examine the steady-state angle obtained from the response.

### 4.5.2 In-Lab Experiment

1. Make sure the QNET_DCMCT_Position_Control.vi. is open and configured as described in Section 5.4. **Make sure the correct *Device* is chosen.**
2. Run the QNET_DCMCT_Position_Control.vi. You should see the DC motor rotating back and forth.
3. In the *Signal Generator* section set:
   - Amplitude = 0 rad
   - Frequency = 0.40 Hz
   - Offset = 0 rad
4. In the *Control Parameters* section set:
   - kp = 2.0 V/rad
   - ki = 0.0 V/(rad.s)
   - kd = 0.02 V.s/rad

5. Apply the disturbance by clicking on the *Disturbance* toggle switch situated below the *Signal Generator*.

6. Examine the effect of the disturbance on the measured position. Attach a response of the motor position when the disturbance is applied, record the obtained steady-state angle, and compare it to the value estimated in Step 4.

7. Turn OFF the *Disturbance* switch

8. In the *Control Parameters* section set:

   - kp = 2.0 V/rad
   - ki = 2.0 V/(rad.s)
   - kd = 0.02 V.s/rad

9. Apply the disturbance by clicking on the *Disturbance* toggle switch.

10. Examine the effect of the disturbance on the measured position. Explain the difference of the disturbance response with the integral action added and compare to the result you obtained in Step 4.

11. Stop the VI by clicking on the *Stop* button.

## 4.6 Results

| Description | Symbol | Value | Unit |
|---|---|---|---|
| **Section 4.4: PD Control Design** | | | |
| Model gain used | $K$ | | rad/s |
| Model time constant used | $\tau$ | | s |
| Proportional gain | $k_p$ | | V/rad |
| Derivative gain | $k_d$ | | V/(rad/s) |
| Measured peak time | $t_p$ | | s |
| Measured percent overshoot | $PO$ | | % |
| **Section 4.5: Response to Disturbance** | | | |
| Measured PD steady-state error | $\theta_{ss,PD}$ | | rad |
| Measured PID steady-state error | $\theta_{ss,PID}$ | | rad |

Table 3: QNET DCMCT Position Control results summary

# 5 SYSTEM REQUIREMENTS

**Required Hardware**

- NI ELVIS II (or NI ELVIS I)
- Quanser QNET DC Motor Control Trainer (DCMCT). See QNET DCMCT User Manual ([1]).

**Required Software**

- NI LabVIEW® 2010 or later
- NI DAQmx
- NI LabVIEW Control Design and Simulation Module
- *ELVIS II Users*: ELVISmx installed from ELVIS II CD.
- *ELVIS I Users*: ELVIS CD 3.0.1 or later installed.

■ **Caution: If these are not all installed then the VI will not be able to run!** Please make sure all the software and hardware components are installed. If an issue arises, then see the troubleshooting section in the QNET DCMCT User Manual ([1]).

## 5.1 Overview of Files

| File Name | Description |
|---|---|
| QNET DCMCT User Manual.pdf | This manual describes the hardware of the QNET DC Motor Control Trainer system and how to setup the system on the ELVIS. |
| QNET DCMCT Workbook (Student).pdf | This laboratory guide contains pre-lab questions and lab experiments demonstrating how to design and implement controllers on the QNET DCMCT system LabVIEW®. |
| QNET_DCMCT_Modeling.vi | Run DC motor in open-loop. |
| QNET_DCMCT_Speed_Control.vi | Control speed of DC motor load using a proportional-integral (PI) compensator. |
| QNET_DCMCT_Position_Control.vi | Control position of DC motor load using a proportional-integral-derivative (PID) compensator. |

Table 4: Files supplied with the QNET DCMCT Laboratory.

## 5.2 Modeling Laboratory VI

The DCMCT Modeling VI, shown in Figure 5.1 and Figure 5.2, runs the DC motor in open-loop and plots the corresponding speed and input voltage responses. This VI can be used to take speed and voltage measurements of the responses, as illustrated in Figure 5.2, and runs a simulation of the DC motor in parallel. Table 5 lists and describes the main elements of the QNET-DCMCT Modeling virtual instrument front panel. Every element is uniquely identified through an ID number and located in figures 5.1 and 5.2.

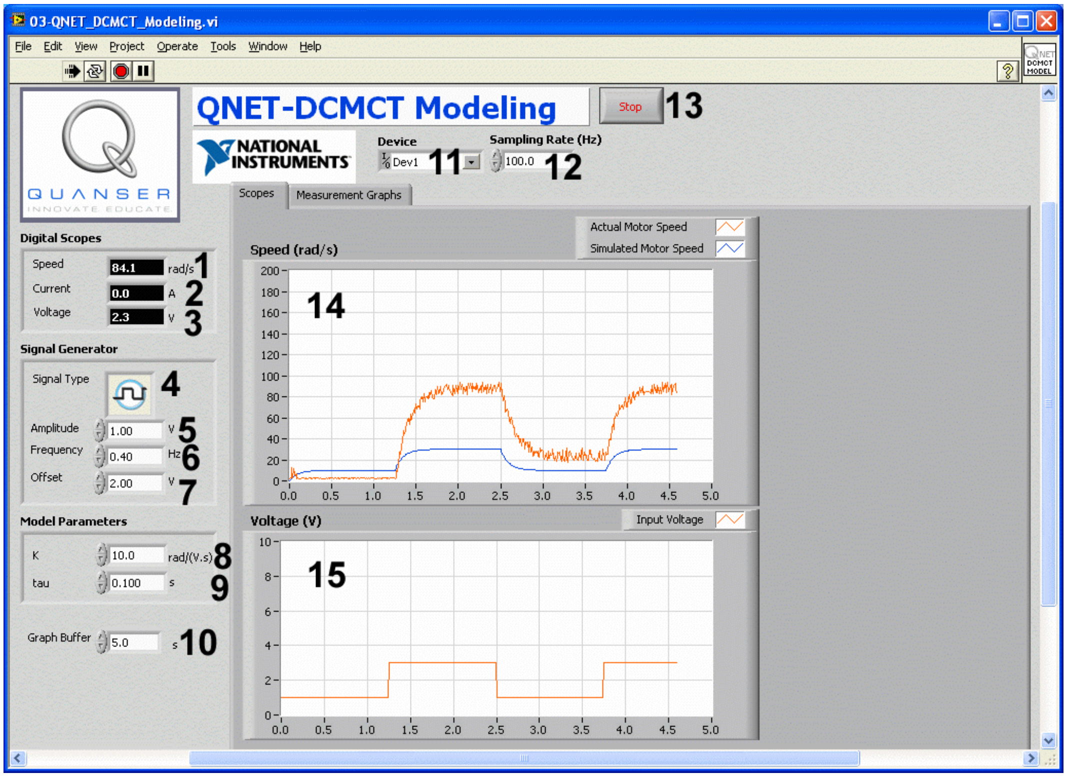


Figure 5.1: QNET-DCMCT Modeling virtual instrument.

## 5.3 Speed Control Laboratory VI

In the QNET DCMCT Speed Control VI, a proportional-integral compensator is used to control the speed of the motor. The PI control also includes set-point weight. Table 6 lists and describes the main elements of the QNET-DCMCT Speed Control virtual instrument user interface. Every element is uniquely identified through an ID number and located in Figure 5.3.

## 5.4 Position Control Laboratory VI

The QNET DCMCT Position Control VI controls the position of the motor using a proportional-integral-derivative controller. The main elements of the VI front panel are summarized in Table 7 and identified in Figure 5.4 through the corresponding ID number.

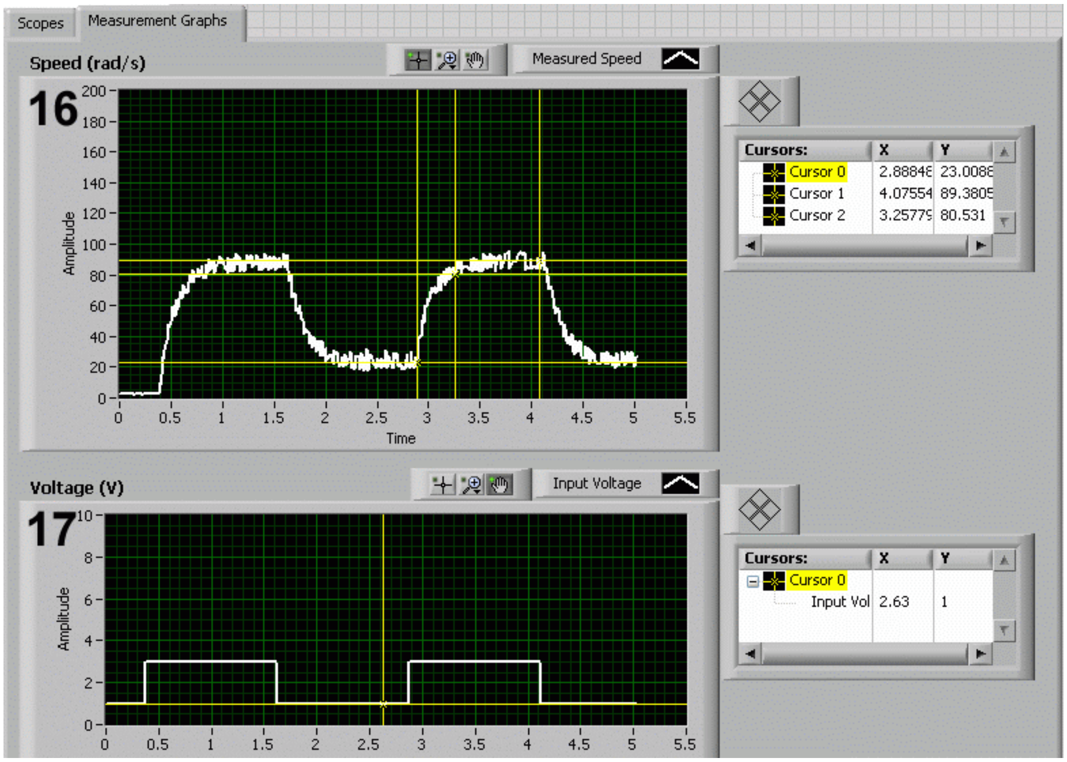


Figure 5.2: QNET DCMCT Modeling VI: *Measurement Graphs* tab selected.

| ID # | Label | Symbol | Description | Unit |
|---|---|---|---|---|
| 1 | Speed | $\omega_m$ | Motor ouput speed numeric display. | rad/s |
| 2 | Current | $I_m$ | Motor armature current numeric display. | A |
| 3 | Voltage | $V_m$ | Motor input voltage numeric display. | V |
| 4 | Signal Type | | Type of signal generated for the input voltage signal. | |
| 5 | Amplitude | | Generated signal amplitude input box. | V |
| 6 | Frequency | | Generated signal frequency input box. | Hz |
| 7 | Offset | | Generated signal offset input box. | V |
| 8 | K | $K$ | Motor model steady-state gain input box. | rad/(V.s) |
| 9 | tau | $\tau$ | Motor model time constant input box. | s |
| 10 | Graph Buffer | | Buffer length of graph data. | s |
| 11 | Device | | Selects the NI DAQ device. | |
| 12 | Sampling Rate | | Sets the sampling rate of the VI. | Hz |
| 13 | Stop | | Stops the LabVIEW VI from running. | |
| 14 | Scopes: Speed | $\omega_m$ | Scope with measured (in red) and simulated (in blue) motor speeds. | rad/s |
| 15 | Scopes: Voltage | $V_m$ | Scope with applied motor voltage (in red). | V |
| 16 | Measurement Graphs: Speed | $\omega_m$ | Graph displays buffered measured motor speed after VI is stopped. | rad/s |
| 17 | Measurement Graphs: Voltage | $V_m$ | Graph displays buffered input voltage used after VI is stopped. | V |

Table 5: QNET DCMCT Modeling VI Components

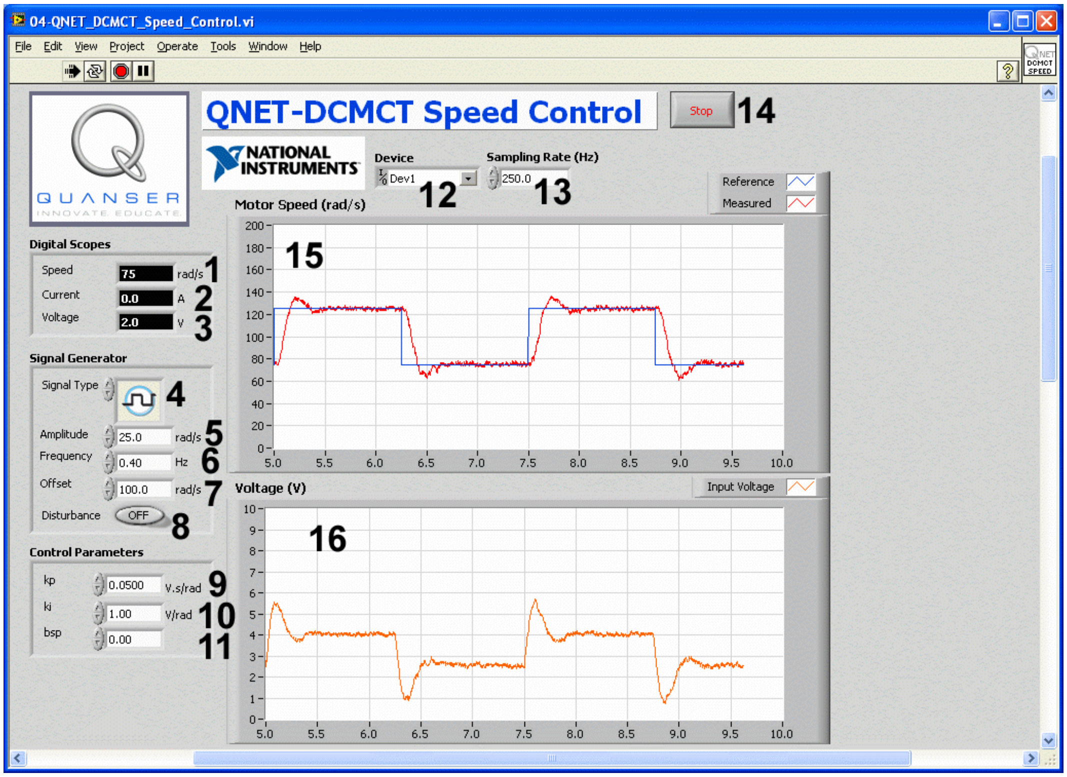


Figure 5.3: QNET DCMCT Speed Control VI.

| ID # | Label | Symbol | Description | Unit |
|---|---|---|---|---|
| 1 | Speed | $\omega_m$ | Motor ouput speed numeric display. | rad/s |
| 2 | Current | $I_m$ | Motor armature current numeric display. | A |
| 3 | Voltage | $V_m$ | Motor input voltage numeric display. | V |
| 4 | Signal Type | | Type of signal generated for the input voltage signal. | |
| 5 | Amplitude | | Reference speed amplitude input box. | rad/s |
| 6 | Frequency | | Refernce speed frequency input box. | Hz |
| 7 | Offset | | Reference speed offset input box. | rad/s |
| 8 | Disturbance | $V_{sd}$ | Apply simulated disturbance voltage. | V |
| 9 | kp | $k_p$ | Controller proportional gain input box. | V.s/rad |
| 10 | ki | $k_i$ | Controller integral gain input box. | V/rad |
| 11 | bsp | $b_{sp}$ | Controller set-point weight input box. | |
| 12 | Device | | Selects the NI DAQ device. | |
| 13 | Sampling Rate | | Sets the sampling rate of the VI. | Hz |
| 14 | Stop | | Stops the LabVIEW VI from running. | |
| 15 | Speed | $\omega_m$ | Scope with reference (in blue) and measured (in red) motor speeds. | rad/s |
| 16 | Voltage | $V_m$ | Scope with applied motor voltage (in red). | V |

Table 6: QNET DCMCT Speed Control VI Components

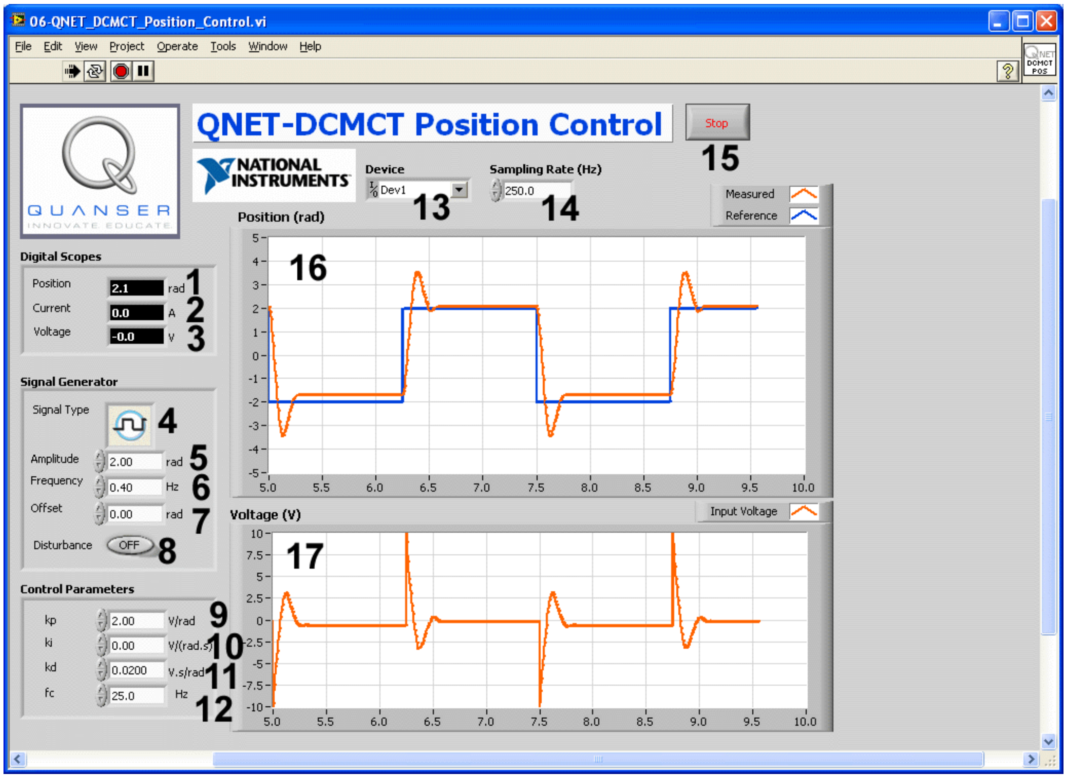


Figure 5.4: QNET DCMCT Postion Control VI.

| ID # | Label | Symbol | Description | Unit |
|---|---|---|---|---|
| 1 | Position | $\theta_m$ | Motor ouput position numeric display. | rad |
| 2 | Current | $I_m$ | Motor armature current numeric display. | A |
| 3 | Voltage | $V_m$ | Motor input voltage numeric display. | V |
| 4 | Signal Type | | Type of signal generated for the input voltage signal. | |
| 5 | Amplitude | | Reference position amplitude input box. | rad/s |
| 6 | Frequency | | Refernce position frequency input box. | Hz |
| 7 | Offset | | Reference position offset input box. | rad/s |
| 8 | Disturbance | $V_{sd}$ | Apply simulated disturbance voltage. | V |
| 9 | kp | $k_p$ | Controller proportional gain input box. | V/rad |
| 10 | ki | $k_i$ | Controller integral gain input box. | V/(rad.s) |
| 11 | kd | $k_d$ | Controller derivative gain input box. | V.s/rad |
| 12 | fc | $f_c$ | Controller high-pass filter cutoff frequency. | Hz |
| 13 | Device | | Selects the NI DAQ device. | |
| 14 | Sampling Rate | | Sets the sampling rate of the VI. | Hz |
| 15 | Stop | | Stops the LabVIEW VI from running. | |
| 16 | Position | $\omega_m$ | Scope with reference (in blue) and measured (in red) motor positions. | rad |
| 17 | Voltage | $V_m$ | Scope with applied motor voltage (in red). | V |

Table 7: QNET DCMCT Position Control VI Components

# 6 LAB REPORT

This laboratory contains three groups of experiments, namely,

1. Modeling,
2. Speed Control, and
3. Position Control.

For each experiment, follow the outline corresponding to that experiment to build the *content* of your report. Also, in Section 6.4 you can find some basic tips for the *format* of your report.

## 6.1 Template for Content (Modeling)

**I. PROCEDURE**

1. *Bumptest*
   - Briefly describe the main goal of the experiment.
   - Briefly describe the experiment procedure in Step 5 in Section 2.3.
2. *Model Validation*
   - Briefly describe the main goal of the experiment.
   - Briefly describe tuning the model parameters in step 7 in Section 2.4.

**II. RESULTS**
Do not interpret or analyze the data in this section. Just provide the results.

1. Bumptest plot from step 5 in Section 2.3.
2. Model validation plot from step 5 in Section 2.4.
3. Provide applicable data collected in this laboratory from Table 1.

**III. ANALYSIS**
Provide details of your calculations (methods used) for analysis for each of the following:

1. Find the model steady-state gain in 7 in Section 2.3.
2. Find the model time constant in 8 in Section 2.3.

**IV. CONCLUSIONS**
Interpret your results to arrive at logical conclusions for the following:

1. How well does the model respresent the actual system in step 6 of Section 2.4.

## 6.2 Template for Content (Speed Control)

**I. PROCEDURE**

1. *Qualitative PI Control*
   - Briefly describe the main goal of the experiment.
   - Briefly describe the experimental procedure in Step 5 in Section 3.3.
2. *PI Control According to Specifications*
   - Briefly describe the main goal of the experiment.
   - Briefly describe the experimental procedure in Step 6 in Section 3.4.
   - Effect of changing damping ratio specification in Step 8 in Section 3.4.
   - Effect of changing natural frequency specification in Step 9 in Section 3.4.
3. *Set-Point Weight*
   - Briefly describe the main goal of this experiment.
   - Briefly describe the experimental procedure in Step 6 in Section 3.5.
4. *Tracking Triangular Signals*
   - Briefly describe the main goal of this experiment.
   - Briefly describe the experimental procedure in Step 5 in Section 3.6.

**II. RESULTS**
Do not interpret or analyze the data in this section. Just provide the results.

1. SLD speed control response plot from step 6 in Section 3.4.
2. Provide applicable data collected in this laboratory from Table 2.

**III. ANALYSIS**
Provide details of your calculations (methods used) for analysis for each of the following:

1. Speed control analysis in Step 5 in Section 3.3.
2. Effect of changing proportional gain in Step 7 in Section 3.3.
3. Effect of changing integral gain in Step 10 in Section 3.3.
4. Peak time and percent overshoot of SLD speed control response in Step 7 in Section 3.4.
5. Effect of changing set-point weight in Step 6 in Section 3.5.
6. Effect of changing integral gain on tracking error in Step 7 in Section 3.6.

**IV. CONCLUSIONS**
Interpret your results to arrive at logical conclusions for the following:

1. Whether the SLD speed controller meets the specifications in Step 7 in Section 3.4.
2. Explain why there is steady-state error in the system in Step 5 of Section 3.6.

## 6.3 Template for Content (Position Control)

**I. PROCEDURE**

1. *Qualitative PD Control*
    - Briefly describe the main goal of the experiment.
    - Briefly describe the experimental procedure in Step 6 in Section 4.3.
2. *PD Control According to Specifications*
    - Briefly describe the main goal of the experiment.
    - Briefly describe the experimental procedure in Step 5 in Section 4.4.
    - Effect of changing damping ratio specification in Step 7 in Section 4.5.
    - Effect of changing natural frequency specification in Step 8 in Section 4.5.
3. *Response to Load Disturbance*
    - Briefly describe the main goal of this experiment.
    - Briefly describe the experimental procedure in Step 6 in Section 4.5.

**II. RESULTS**
Do not interpret or analyze the data in this section. Just provide the results.

1. Position control response plot from step 5 in Section 4.4.
2. PD disturbance response plot from step 6 in Section 4.5.
3. PID disturbance response plot from step 10 in Section 4.5.
4. Provide applicable data collected in this laboratory from Table 3.

**III. ANALYSIS**
Provide details of your calculations (methods used) for analysis for each of the following:

1. Position control analysis in Step 6 in Section 4.3.
2. Steady-state error in Step 7 in Section 4.3.
3. Effect of changing derivative gain in Step 9 in Section 4.3.
4. Peak time and percent overshoot of SLD speed control response in Step 6 in Section 4.4.

**IV. CONCLUSIONS**
Interpret your results to arrive at logical conclusions for the following:

1. Whether the SLD speed controller meets the specifications in Step 6 in Section 4.4.
2. Does the measured steady-state error using a PD control match what is expected in Step 6 of Section 4.5.
3. Does the measured steady-state error using a PID control match what is expected in Step 10 of Section 4.5.

## 6.4 Tips for Report Format

**PROFESSIONAL APPEARANCE**

- Has cover page with all necessary details (title, course, student name(s), etc.)
- Each of the required sections is completed (Procedure, Results, Analysis and Conclusions).
- Typed.
- All grammar/spelling correct.
- Report layout is neat.
- Does not exceed specified maximum page limit, if any.
- Pages are numbered.
- Equations are consecutively numbered.
- Figures are numbered, axes have labels, each figure has a descriptive caption.
- Tables are numbered, they include labels, each table has a descriptive caption.
- Data are presented in a useful format (graphs, numerical, table, charts, diagrams).
- No hand drawn sketches/diagrams.
- References are cited using correct format.

# REFERENCES

[1] Quanser Inc. *QNET DC Motor Control Trainer User Manual*, 2011.